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# Influence of reinforcement buckling on the seismic performance of reinforced concrete columns

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ABSTRACT

The buckling of longitudinal reinforcing steel is one of the most important failure stages of reinforced concrete (RC) flexural specimens under seismic loading. To study the influential factors in longitudinal buckling, a simplified buckling model for columns with rectangular and circular cross sections has been developed based on stability theory. In this study, 6 rectangular and 5 circular RC columns with different reinforcement yield strengths and configurations were tested under constant axial and reverse horizontal loads. The simplified buckling model was verified, and the influence of reinforcement buckling on the seismic performance of RC columns was studied. The results indicate that the buckling model can provide a good estimate of the buckling length of the longitudinal bars. The length-to-diameter ratio ($L/D$) of the longitudinal bars is the key factor that influences the seismic performance of RC columns. The simplified buckling model can reflect the influential factors of bar buckling and can provide guidelines for the seismic design of RC columns.

## 1. Introduction

In the seismic context, reinforced concrete (RC) columns may experience significant lateral deformation of the longitudinal reinforcing bars accompanied by spalling of the cover concrete. For RC members with or without low levels of axial load, the primary failure mechanism is the buckling of the longitudinal reinforcement and the subsequent fracturing of that steel upon the lateral reversal load [1,2]. Hence, buckling of the longitudinal bar has a significant influence on the seismic response of concrete members [3,4].

Based on experimental results of uniaxial monotonic and cyclic tests of reinforcing steel, various stress–strain relationships of reinforcing bars [5–14], including buckling, have been proposed. All of these relationships suggest that the stress–strain constitutive relation of a bare bar is a function of the length-to-diameter ratio ($L/D$). Hence, it is essential to calculate the buckling length of longitudinal bars to obtain a stress–strain model of reinforcing steel for estimating the seismic performance of RC columns. It is generally considered that the buckling length of longitudinal reinforcement is equal to the distance between stirrups, which is called local buckling of the reinforcement. According to the experimental results from monotonic axial compression [15–19] and reversed cyclic [20–27] tests of RC members, the buckling length of longitudinal bars likely varies from one to several times the tie spacing, which is called global buckling of the reinforcement by Massone and López [28]. Thus, the buckling length is not completely determined by the tie spacing but also by the flexibility of the reinforcement (longitudinal and transversal).

The use of high-strength steel bars in RC elements offers many advantages, such as reducing congestion, easing design and construction constraints, minimizing construction time, and reducing initial and life-cycle costs. However, the use of high-strength material as longitudinal and transverse reinforcement in concrete columns will result in relatively smaller bar diameters and greater stirrup spacing, which commonly results in a reduction of the reinforcement stiffness. Consequently, the use of high-strength steel bars influences the reinforcement buckling and seismic performance of RC columns.

Many researchers have investigated the seismic performance of RC columns reinforced with different strength longitudinal and transverse reinforcements [29–35]. However, very few studies have taken the influence of longitudinal bar buckling into consideration.

In this work, to study the influence of reinforcement buckling on the seismic performance of RC columns, a simplified reinforcement buckling model of longitudinal bars has been developed

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## Nomenclature

| | |
|---|---|
| $\delta$ | maximum lateral displacement of longitudinal bar |
| $\delta_u$ | ultimate drift ratio of RC column |
| $\mu_{\triangle u}$ | displacement ductility |
| $\sigma$ and $\varepsilon$ | steel stress and strain |
| $\sigma_y$ and $\varepsilon_y$ | steel yield stress and yield strain |
| $A$ and $A_{sv}$ | cross section of longitudinal and transverse reinforcement |
| $A_t$ and $A_{gt}$ | strain value of steel specimen at rupture and ultimate stress |
| $D$ and $D_{sv}$ | diameter of longitudinal and transverse reinforcement |
| $E$ | effective elastic modulus of longitudinal bars |
| $E_c$ | elastic modulus of concrete |
| $E_s, E_t, E_u$, and $E_r$ | initial, hardening, unloading and reduced tangent modulus of reinforcement |
| $E_{sys}$ and $E_N$ | total and normalized energy dissipation of RC column |
| $F_c$ and $F_r$ | lateral restraint force of longitudinal bar provided by rectangular and circular hoop |
| $F_m$ and $\triangle_m$ | maximum lateral force and corresponding displacement of RC column |
| $F_u$ and $\triangle_u$ | ultimate displacement and corresponding lateral force of RC column |
| $F_y$ and $\triangle_y$ | yield lateral force and yield displacement of RC column |
| $f_y$ and $f_u$ | yield stress and ultimate stress of steel specimen |
| $H$ | height of RC column |
| $I$ | inertia moment of longitudinal bar |
| $k$ | effective spring stiffness |
| $k_r$ and $k_c$ | effective spring stiffness corresponding to rectangular and circular hoop |
| $L$ | buckling length of longitudinal bar |
| $L_X$ and $L_Y$ | length of rectangular hoop parallel and perpendicular to the load direction |
| $n$ | ratio between buckling length of longitudinal bars and stirrups spacing |
| $P$ | axial load applied to longitudinal bar |
| $P_c, P_0$ | axial load applied to RC column and design compressive bearing capacity of RC column |
| $P_t, P_u$, and $P_{cr}$ | axial load of longitudinal bar corresponding to tangent modulus of $E_t, E_u$ and $E$ |
| $R$ | diameter of spiral stirrup |
| $S$ | stirrup spacing |
| $U$ | total energy stored in the longitudinal bar |
| $U_{strain}, U_{spring}$, and $U_{bar}$ | strain energy, energy stored in the springs and energy associated with the shortening of reinforcing bar |
| $v$ | lateral displacement of longitudinal bar |

based on stability theory. Factors such as transverse confinement and section configuration that influence buckling have been studied using reverse cyclic loading tests on 6 rectangular and 5 circular RC columns.

## 2. Research significance

Less reinforcement may affect the buckling of longitudinal bars in association with the replacement of ordinary reinforcement with high-strength reinforcement. The effects of reinforcement buckling should therefore be considered when high-strength steel bars are used in RC columns. In this study, a simplified buckling model is developed to estimate the buckling behavior of longitudinal bars. According to the parameter analysis and experimental verification of the reinforcement buckling model, we are able to identify the factors that influence the buckling of the longitudinal bar and the sensitivity of each parameter to optimize the use of high-strength reinforcement in seismic regions and effectively estimate the seismic performance of concrete columns.

## 3. Simplified global buckling model

Bresler and Gilbert [36] first studied the buckling of longitudinal reinforcement in concrete columns and proposed a method for predicting the critical load and buckling shape to design lateral ties that are sufficiently rigid to avoid global buckling. Scribner [15] assumed that the reinforcement would buckle in a mode shape that spanned three tie intervals and indicated that the buckling of longitudinal bars could be influenced by confining the tie size and spacing. Pipia et al. [37] considered the inelasticity of longitudinal bars in the buckling process and introduced the reduced modulus $E_r$ to the instability analysis. Pantazopoulou [38] proposed the nonlinear Euler buckling model to analyze the stability of reinforcing bars, including the effects of load reversals, and developed alternative requirements for reinforcement stability that recognize the interaction between displacement ductility demand in the critical section, tie effectiveness, limiting concrete strain, bar size, and tie spacing based on data compiled from over 300 RC columns.

Dhakal and Maekawa [39] proposed a simple and reliable global buckling model of longitudinal reinforcing bars based on stability analysis. This model considers both the geometric and mechanical properties of the longitudinal reinforcing bars and lateral ties and was verified through various experimental cases of rectangular columns. Massone and López [28] studied the global buckling behavior of longitudinal reinforcements under compression based on a concrete plasticity fiber model with four plastic hinges and validated the buckling model using experimental results. These two methods both consider bars directly constrained by stirrup bars or intermediate bars without directly constraint have similar buckling models. However, the experimental results from Kato [16,17] showed that intermediate bars are vulnerable to buckling.

Zong and Kunnath [40] developed a simplified "beam-on-springs" model for a circular RC column wherein the longitudinal reinforcing bar was simulated as a flexural member and the transverse reinforcement was represented by springs at the location of each transverse bar. In addition, an efficient material model for reinforcing steel that implicitly incorporates the degrading effects of bar buckling was developed in reinforced concrete (RC) columns [41].

This paper further develops the "beam-on-springs" buckling model to better estimate the buckling length of longitudinal bars for different sections and confinement types. The effective elastic modulus is introduced to modify the elastic modulus of the longitudinal bars based on stability theory, as well as the effective spring stiffness of lateral ties for different section and confinement types.

### *3.1. Assumptions*

The deformation shape of the buckled bar is assumed to be a cosine curve that satisfies the fixed boundary condition, and the restraining mechanism of the lateral ties is assumed to be the